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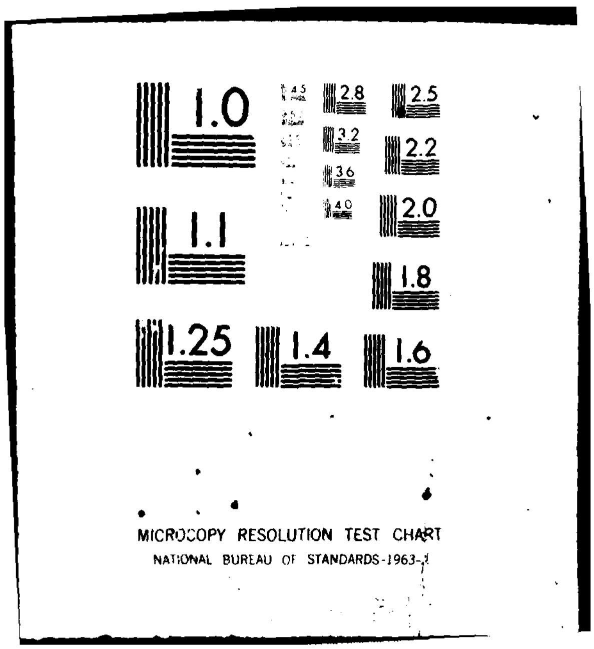
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During the past two years, we directed our metallurgical study of the embrittlement of bore surfaces toward the examination of the composition of large-calibre gun barrel surfaces via the combined SEM/SAM (Scanning Electron Microscope/Scanning Auger Microprobe) techniques. In this final report, we outline the principal results of this study.

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TITLE OF PROPOSAL: The Embrittlement of Alloys Under Impulse Thermal, Pressure and Chemical Conditions

CONTRACT OR GRANT NUMBER: DAAG29-79-G-0038

NAME OF INSTITUTION: Princeton University

AUTHOR OF REPORT: Dr. A. Kahn

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J.L. Yeh, post-doctoral research
John Carelli, graduate student

During the past two years, we directed our metallurgical study of the embrittlement of bore surfaces toward the examination of the composition of large-calibre gun barrel surfaces via the combined SEM/SAM (Scanning Electron Microscope/Scanning Auger Microprobe) techniques. In this final report, we outline the principal results of this study.

On the uncoated bore surface of a worn 5" naval gun, which exhibited a pebbled texture after being fired with bag propellants containing a TiO_2 wear-reducing additive, we observed the segregations of Ti and O at the surface. From the perfect correlation between the Ti and O Auger elemental micrographs, we could identify the formation of the TiO_2 compound and specify its preferential location at the boundaries between the pebble domes of the embrittled steel.[1] The elemental distribution along the cracks propagating in depth away from the surface was also profiled via SAM technique. The possibility of detecting surface segregation of impurities has a considerable importance: the presence of contaminants at grain

boundaries is a very crucial parameter in determining the fatigue characteristics of a material, since the nature of the granular interface influences strongly the propagation of cracks.[2] The grain boundary is most probably a high energy region and it is expected that segregation of impurities could occur at this region. If the increase in contamination is substantial, the cohesion of the region can be seriously reduced.[3] The segregation of impurities is always responsible for embrittlement of materials.

In a second study, we have examined six specimens sectioned from the worn bore of a 105 mm M-68 tank gun which had been fired about 500 rounds with M490 HT propellant containing no additives. The original location of the specimens along the gun tube is illustrated in Fig. 1. The bore surface of the gun had been partially coated with chromium before use. The 250 μm thick Cr layer had been electroplated onto the first three sections, as indicated on Fig. 1. Ordinary optical images of those six specimens are shown in Fig. 2. The machine-cut grooves and diamond scratches are clearly seen, shining in contrast to the darker background of the real bore surface.

The surface of the Cr-coated portion showed no spalling (e.g. section 1 and 2) and was covered with a continuous layer of inorganic salts consisting mainly of ZnO derived from the Zn plating of the propellant casing.[1] The other salts found on the surface included fluorides of K and Ca and sulfur-containing compounds. The topography of section 3 was unique, displaying localized areas of spalling (see Fig. 2). At the unspalled region, the inorganic deposits on top of the Cr layer was found to be Al_2O_3, ZnS (<u>not</u> ZnO), KF and CaF_2. However, ZnO, Al_2O_3 and sulfur-containing compounds were detected directly on the gun steel substrate in the spalled areas. These areas also showed very fine cracks detected under microscope examination.

On the uncoated specimens (section 4 thru 6), which exhibited the characteristic pebbled texture observed on the naval gun mentioned earlier, we detected a layer of ZnO, K_2S and CaS on the pebbled domes. The F and Al originated from the cryolite additive (Na_3AlF_6) to the propellant, the S from the black powder, and the K from the black-powder igniter. In Table 1, we summarize the compositions and thicknesses of these inorganic, propellant induced, salt layers.[4]

By fracturing the specimen at liquid nitrogen temperature, the formation of the preferentially broken faces exposes the weak areas of the materials. Therefore, one can study the initiation and propagation of the cracks which are the fatigue characteristics of the gun steel. The cooling of the specimens to low temperature was required in order to obtain brittle fractures, the steel being rather ductile at room temperature.[3] The electroplated Cr film was found to be thinned after the firing cycles to about 200 μm in the section close to the origin of the rifling, and to about 150 μm in the region located 10 inches further down the gun tube where spalling is evident. The Cr coating was also found to be very brittle and inhomogeneously contaminated primarily with C and Ca. As demonstrated by the fracture study, the presence of these impurities in the Cr layer produced many irregularly shaped steps or islands at the surface. However, the Cr-steel interface was not found in any way mechanically weakened. No evidence of flaking of the Cr at the Cr-steel interface has been observed. Furthermore, the fracture studies of the specimen also disclosed very clearly a metallurgically-altered steel layer extending about 250 μm below the bore surface, the Auger images of which exhibit a great deal of C and K as opposed to the chemical composition of the unaltered steel substrate showing little C and no K. The interface between the altered and the unaltered layers does not always part when the specimen undergoes a shear force. Up to now, there is still no precise understanding of the origin of such a metallurgical alteration. It is, however, believed to be due to both thermal and mechanical effects,[5] the thermal effect probably playing the essential role.

The cross sections of the fractured, coated specimens showed that all have a continuous, well-defined layer of Cr with considerable thickness (at least 150 μm, see Table 1). However, although the cross sections of the uncoated specimens showed no significant distribution of Cr, some small Cr blocks were observed under a thin film of Fe and inorganic salts (up to 30 μm thick). At the edge where the machine used to cut these specimens left deep structural defects, the covering layer of iron has been damaged and the Cr is exposed. It is probably the combined sweeping action of the high-velocity combustion gases and the mechanical friction of the casing that brought those small Cr blocks from the spalled coated region down to

the uncoated portion. They were then mixed with the melted steel during each firing round under high temperature and pressure.

Therefore, on the basis of these results, one might speculate that the surface conditions (either temperature or pressure, or both) of section 3 during each ballistic cycle are the most severe among the first six sections. In addition to its unique topography, section 3 differs from the others most significantly by its surface combustion products. The reason must be the particular strong temperature and pressure conditions, higher in this area of the gun than anywhere else. This particularly violent environment favors the oxidation of Al instead of the one of Zn as observed in other parts of the gun. The Zn and S are swept further down the gun.

Such a drastic and violent environment at section 3 is also directly responsible for the observed removal of material from the bore surface. The major role of the Cr coating can be pictured as follows: the Cr serves as a solid skin over a momentarily melted substrate,[1] and prevents the steel from being subjected to the full effect of the shear force of the ejected shell and the turbulent flow of the combustion gases. The Cr coating is therefore essential in prolonging the gun-barrel life although the reasons why some spalling occurs in relatively small regions is still unknown.

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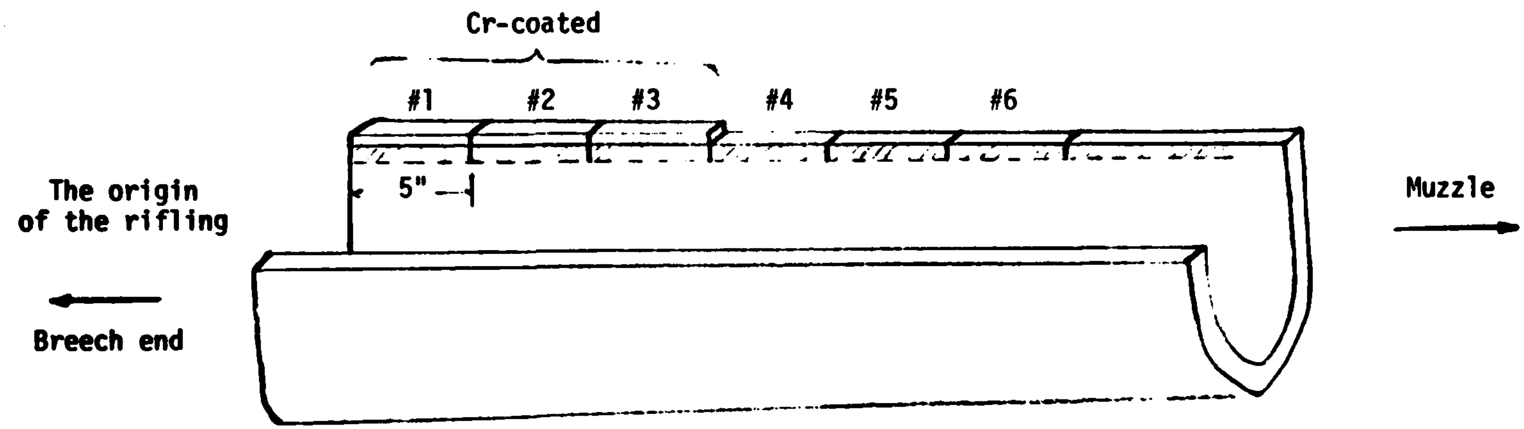

Fig. 1 Positions of the specimens sectioned from a worn Cr-plated 105 mm M68 tank gun which was fired 493 rounds with M490HT without additives. The original thickness of Cr coating is 250 µm.

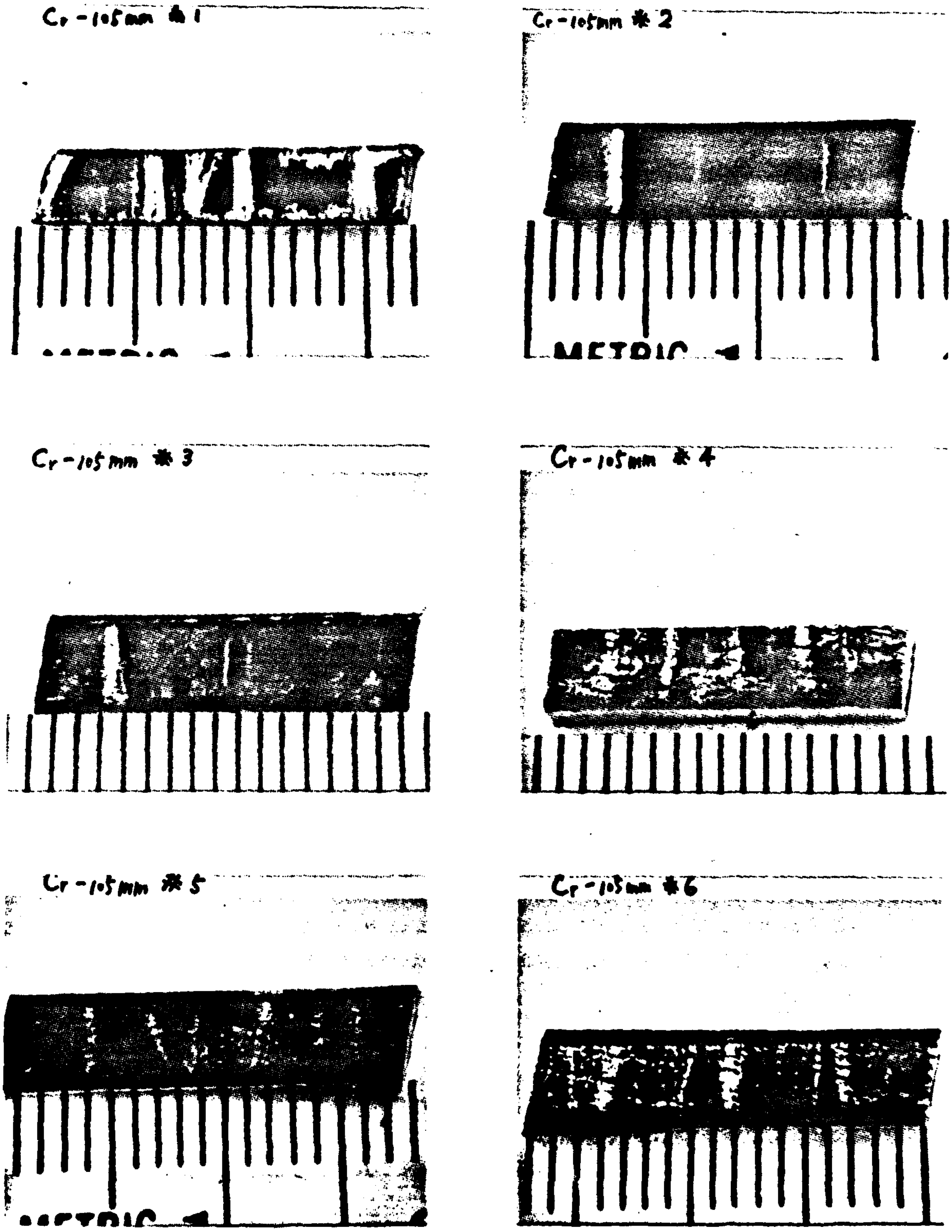

Fig. 2 Optical images of the six studied specimens. One small unit of the attached scale is 1 mm long.

Table 1

Combustion-reaction products deposited on the bore surface of the six studied specimens whose locations are illustrated in Fig. 1

Cr-coated				uncoated			
Specimen #1	Specimen #2	Specimen #3		Specimen #4	Specimen #5	Specimen #6	
		unspalled	spalled				
ZnO S-compounds	ZnO S-compounds	Al_2O_3 flourides ZnS	Al_2O_3 ZnO K_2S CaS	Al_2O_3,ZnO K_2S,CaS [flourides]*	ZnO K_2S,CaS [flourides]*	ZnO K_2S,CaS [flourides]*	~20 μm
Cr (~250μm)	Cr	Cr (~150μm)		(altered steel layer)			~250 μm
				(unaltered steel substrate)			

*F Auger signal is relatively weak